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Three Dimensional Optical Time Delay Units for Radar

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ABSTRACT

2-D SLM based optical time delay units (OTDUs) are introduced for radar and wideband signal processing applications. In particular, the mature nematic liquid crystal (NLC) SLM technology is considered for the proposed architectures. A 1X2 optical switch is demonstrated using a parallel-rub birefringent-mode NLC cell, a bulk optics cube polarizing beamsplitter, and a sheet polarizer. Switch measurements taken at 633 nm show a > 3400 : 1 or > 35 dB output port optical isolation. The 1 X 2 NLC switch is used to build a 1-bit , 3.33 ns duration free-space OTDU using mirrors and total internal reflection corner prisms. The unit demonstrated a > 30 dB optical signal-to-noise ratio for both delay and no-delay positions.

2. INTRODUCTION

Switched optical delay lines can be used to control wide instantaneous bandwidth phased array antennas. Recently, we proposed the use of nematic liquid crystal (NLC) optical switching arrays for making a free-space optical time delay structure using cascaded OTDUs [1-3]. It is desirable to have OTDUs that are low in cost, have high optical isolation (> 30 dB), and low optical insertion loss (< 1 dB). In addition, the OTDUs must be reliable, easy to assemble and test, have a stackable design for easy channel expansions and upgrades, and be lightweight. Given the desired requirements for the OTDU, in this paper, we explore and experimentally demonstrate the possibility of a NLC-based OTDU. The motivation at present for going to NLC technology has to do with the great success of NLC displays, where high performance arrays have be built and fabricated on a large scale (see Fig.1). This great maturity of NLC technology lends itself to low fabrication costs and well understood NLC fabrication procedures that can lead to high performance devices in terms of high optical isolation (> 1000 :1) and low optical loss (e.g., < 1 dB) for the phased array application. Moreover, the slow temporal response (e.g., 50 ms) of commercial display-type NLCs have been greatly improved (e.g., 1 ms) using the transient nematic effect with parallel-rub birefringent mode NLCs. Thus, using a two channel time multiplexed approach for radar control, a millisecond NLC response time could provide a scanning rate of 1000 radar beams/s that is adequate for many radar applications [4]. Nevertheless, the SLM-based OTDUs discussed in this paper apply to other SLM technologies such as ferroelectric liquid crystal SLMs. Although the focus of this paper is the application of OTDUs for the control of phased array antennas, other applications where delay lines are required are also possible such as wideband transversal filtering and radar testing.

3. THE NOVEL OPTICAL DELAY LINES

There are several ways in which 2-D SLMs can be used to form free-space or fiber-based switched OTDUs. We describe three approaches as follows.

The Cascaded Free-Space Type:

Fig.2 shows a version of the cascaded free-space type multichannel optical switched delay line. Time delay is obtained through free-space propagation of optical beams over compact (< 30 cm path) cascaded optical delay units. Freespace paths are appropriate when short (< 4 ns) time delays are required for the most significant bit in a binary serial delay line structure. Imaging lenses can be used to minimize optical losses from beam spreading and diffraction effects. Moreover, longer delays are achieved by folding the free-space paths or by inserting fiber loops. The input to the OTDUs is a 2-D array of intensity modulated linearly polarized collimated pencil beams. Each beam corresponds to an independent channel in the multichannel OTDU architecture. 2-D pixelated NLC arrays are placed before each delay path to act as 90° optical polarization rotators. Each NLC array contains all the time delay channels on one NLC substrate. The PBS after the NLC array directs the light into its appropriate delay path, depending on the on/off state of the corresponding NLC pixel. By placing a cascade of such NLC OTDUs, it is possible to make a low insertion loss, high isolation switchable optical delay line. Note that before the output port of the delay line, another 2-D NLC array and polarizer are placed that provide analog amplitude calibration across the channels.

The Single Optical Switching Layer Array Type:

Fig.3 shows a novel, single NLC array substrate, multichannel free-space optical delay line design. In this case, a single large substrate is used for fabricating all the NLC pixels required for the delay line. Both polarization rotation functions and amplitude calibration are performed on NLC arrays on the same substrate. This OTDU design is possible because of the large area NLC display fabrication techniques that have produced over 14 inch diagonal displays.

The Folded Fiber Type:

Fig.4 show the folded-fiber type multichannel optical switched delay line. In this case, separate lengths of PM-fiber are wrapped around a single PBS to form switched delays. The input to the unit is a 1-D array of intensity modulated linearly polarized collimated pencil beams that correspond to the number of independent time delay channels in the system. This 1-D array of beams passes through a 1-D NLC array that acts as an array of optical polarization rotators. Before the looped fibers are fed back to the PBS, the light passes through a N X M pixel 2-D NLC array that provides the switching stages for the N-bits of the M parallel delay lines. A cylindrical lens directs the M delayed light signals towards a 1-D M-element GRIN lens-fiber array that provides the M output beams of the unit. Again, a M-element 1-D NLC array and a polarizer before the GRIN lens-fiber array provides the amplitude calibration for the multichannel unit. The use of low loss fibers in any of the above OTDUs provides a compact mediun for very long time delays, such as needed for very large antenna arrays or radar testing applications. See Table.1 for a comparison of the various delay lines.

4. EXPERIMENTS

Fig.5 shows the structure of a typical OTDU using a NLC SLM, sheet polarizers, cube PBSs, total internal reflection (TIR) corner prisms, and appropriate free-space input/output ports. The optical switching operation is based on polarization rotation of light beams by an electrically controlled birefringent medium, in this case, NLCs. In particular, linearly polarized light is incident at 45 degrees to the nematic director of the NLC cell (see Fig.6) . On applying a voltage to the NLC cell, a relative optical phase shift can be introduced between the ordinary and extraordinary ray components of the incident light. By introducing a 180 degree phase shift, the linear polarization of the incident light can be rotated by 90 degrees.Thus, the NLC cell acts as a programmable half-wave plate. When such a NLC cell is coupled with a PBS such as a cube PBS, light of one linear polarization passes straight through the cube PBS, while light of the orthogonal linear polarization is spatially deflected by 90 degrees by the cube PBS. In this way, a NLC cell with a cube PBS in cascade arrangement forms a 1 X 2 optical switch. This 1 X 2 switch is the fundamental building block of the reversible OTDUs discussed earlier.

The NLC cells in the OTDUs are either on (rotate polarization) or off (no rotation of linear polarization). The sheet polarizers with certain fixed polarization directions (either vertical or horizontal) suppress unwanted polarized light, and act as noise removal filters. In particular, commercial cube PBS's have poor (e.g., 20:1) optical extinction ratios at their deflected output ports. This problem is alleviated by using an output sheet polarizer. If fibers are used for carrying the information coded optical signals in the time delay paths, the fiber must be polarization preserving. High quality (e.g., 40 dB extinction) polarization preserving single mode fibers are commercially available from Andrew Corporation. These fibers are coupled to GRIN-rod fiber lenses that generate or accept collimated, linearly polarized light beams that travel through the optical switch. Typical dimensions for the commercially available components are 12.7 mm side cubes, 2 mm diameter fiber-GRIN lenses, and 12.7 mm side prisms. The other components can be easily designed to accomodate the commercial components. The typical NLC cell is 6 μm in thickness. For a 12.7 mm X 12.7 mm cube, using a 1 mm optical channel pitch in the OTDU, 144 independent input/output channels can be handled in a lightweight package. Note that 50 mm side cubes are commercially available if a larger number of optical channels is required.

The OTDUs can operate over the visible and near infrared bands of the optical spectrum (400 nm to 1600 nm). The 1 X 2 switch is well suited for the 1.3 μm laser wavelength used in high speed communications using distributed feedback (DFB) semiconductor lasers or externally modulated links using diode-pumped solid state YAG lasers. In this case, high quality Polacor near infrared sheet polarizers from Corning Inc. can provide very high (> 10,000 :1) optical extinction ratios. For optimum low optical loss operation, all components, that is, the cubes, the NLC SLMs, the prisms, the sheet polarizers, and the input/output coupling optics (including fiber assemblies) have to be antireflection (AR) coated for the desired wavelength. Note that with good AR coatings, commercial optical components can have 1 % or less optical losses due to surface/Fresnel reflections. Table 2 shows the measured percentage transmission at 633 nm wavelength for the various commercial components used in the experiments

Note that the Melles Griot sheet polarizer made from a plastic dichroic polarizing sheet sandwitched between two strain free glass plates has no antireflection coating, causing a high optical loss. This loss can greatly be reduced by AR coatings. Transmission measurements are also taken for NLC cells fabricated at GECRD that do not have AR coatings. Fig.7 shows a transmission vs. wavelength graph generated for the visible and near IR spectrum using a spectrometer for a 6 μm thick NLC cell using ordinary glass material similar to Corning 7059 glass. The glass is not AR coated so there is a nominal 4 % loss at each outside surface. Measurements show a 89 % transmission at 1.3 μm optical wavelength. If the cell were AR coated, the transmission should be 2 X 4 =8 % more or 97 %. Note that no attempt was made to optimize the optical coating thickness inside the cell for maximum transmission. If such optimization is implemented, the NLC cell transmission can further be increased, indicating that NLC SLMs can be very low loss optical components over the visible and near IR region of the optical spectrum.

The 1 X 2 NLC optical switch (shown in Fig.8) that is the building block for the OTDUs is setup in the laboratory. The purpose of the experiment is to measure the optical on/off isolation possible with the 1 X 2 NLC optical switch at its output ports. Linearly (vertically) polarized light from a 14 mW 633 nm He-Ne laser is used as a light source. A Thompson prism PBS used as a polarizer is placed in the laser beam to improve the polarization/extinction ratio of the light. The experiment is carried out using an NLC cell containing the ZLI 3568 NLC mixture from Merck, Germany. This mixture has a birefringence of 1.830 - 1.505 = 0.125 at 589 nm. The cell is driven by a 1 KHz square wave whose amplitude controls the NLC state. Fig.9 shows the normalized data plot of the light out of the two output ports, showing the desired reciprocal behavior. The measured straight beam optical contrast ratio is 9.52 mW / 2.57 μW = 3,704 :1 which is 35.68 dB optical isolation or 71.37 dB rf isolation. The measured 90 degree deflected beam optical contrast ratio is 6.34 mW / 1.84 μW = 3,446 :1 which is 35.37 dB optical isolation or 70.75 dB rf isolation. Note that if the sheet polarizer in the 90 degree deflected optical beam path is removed, the optical contrast ratio drastically drops to 20 : 1. Because a very high percentage of the noise in the deflected beam from a commercial cube PBS is highly polarized (infact it has a linear polarization orthogonal to the desired signal beam polarization from the deflected port), this noise can be greatly suppressed by using a polarizer aligned to the signal beam polarization (which is crossed with the noise). Thus, a cube PBS and an NLC cell with a polarizer can form a very high optical isolation (> 35 dB) 1 X 2 optical switch. When such a switch is used to form the OTDU, very high optical isolation performance (> 30 dB) can be expected. The measured optical insertion loss for the 1 X 2 switch is calculated as follows. For the straight beam, the optical insertion loss is 10 log (9.52 mW / 12.37 mW) = - 1.14 dB. Similarly, for the deflected beam, the optical insertion loss is 10 log (6.34 mW / 12.37 mW) = - 2.9 dB. Note that these optical insertion losses can be greatly improved by careful alignment and using all AR coated optics.

The OTDU in Fig.5 is set-up in the laboratory by adding components to the 1 X 2 NLC switch set-up. For the experiment, one of the TIR prisms shown in Fig.5 is replaced by a pair of 97 % reflectivity mirrors. The single TIR prism used in the experiment had no AR coatings, with a 4 % loss at each entrance and exit air/glass interface (there are two of them). The extra path length travelled by the deflected beam is designed at 1 m that corresponds to a 3.33 ns optical time delay. In order to take measurements from the delayed and undelayed optical signals, it was necessary to separate the two signal beams spatially at the detector plane. This is done by slightly tilting one of the mirrors in the delay path. In this way, the signal and noise contributions for the two settings (delay or no delay) of the OTDU can be measured. For the no delay (or straight beam) setting measured at 1.49 Volts peak NLC drive, the signal contribution was measured as 9.93 mW while the noise contribution coming from the deflected or delayed path was 3.25 μW. Thus, the optical signal-to-noise ratio (SNR) for the OTDU no delay positioned is measured as 10 log (9.93 mW / 3.25 μW) = 10 log 3055 = 34.85 dB. This is equivalent to an electrical SNR of 69.7 dB. The optical insertion loss for this position is -0.95 dB. Next, for the 1 m delay (or deflected beam) setting measured at 0.97 Volts peak NLC drive, the signal contribution was measured as 5 mW while the noise contribution coming from the straight or undelayed path was 5 μW. Thus, the optical signal-to-noise ratio (SNR) for the OTDU delay positioned is measured as 10 log (5 mW / 5 μW) = 10 log 1000 = 30 dB. This is equivalent to an electrical SNR of 60 dB. The optical insertion loss for this position is - 3.9 dB.

Fig.10 shows an alternate configuration for an OTDU that is set-up in the laboratory. In this case, the pair of mirrors (or one of the TIR prisms in Fig.5) used in the earlier OTDU is replaced by a single cube PBS. The second PBS in the OTDU is slightly tilted to separate the delay path and un-delay path beams. The measurements indicate some what improved output SNRs that result from adding another polarization based component that in effect acts as a noise reduction filter. In addition, this optical configuration has an exit port (at the second PBS) for the unwanted light. For the no delay (or straight beam) setting for this OTDU measured at 1.49 Volts peak NLC drive, the signal contribution was measured as 9.26 mW while the noise contribution coming from the deflected or delayed path was 3.08 μW. Thus, the optical signal-to-noise ratio (SNR) for the OTDU no delay positioned is measured as 10 log (9.26 mW / 3.08 μW) = 10 log 3006.5 = 34.8 dB. This is equivalent to an electrical SNR of 69.6 dB. The optical insertion loss for this position is - 1.26 dB. Next, for the 0.5 m delay (or deflected beam) setting measured at 0.97 Volts peak NLC drive, the signal contribution was measured as 4.94 mW while the noise contribution coming from the straight or undelayed path was 3.7 μW. Thus, the optical signal-to-noise ratio (SNR) for the OTDU delay position is measured as 10 log (4.94 mW / 3.7 μW) = 10 log 1335 = 31.26 dB. This is equivalent to an electrical SNR of 62.5 dB. The optical insertion loss for this position is - 4.0 dB.

The NLC cells used in the earlier experiments had large 1 cm X 1 cm pixel regions. To get an idea for the kind of on/off isolation possible with a densely populated NLC SLM, we used a 1500 pixel, 300 μm pixel size, birefringent-mode parallel-rub NLC device fabricated at GECRD (see Fig.11). The gap between the pixels was 15 μm, as this device was fabricated for laser beam steering and optical signal processing applications. For the antenna application, this gap can be very large, e.g., 2 mm, plus the pixel can also be big. The 1500 pixel device is placed as the NLC cell in the arrangement in Fig.8. Using imaging/ 2X magnification optics and a small area (e.g., 500 μm in diameter) photodiode on a high resolution x-y translational stage, the optical on/off isolation of certain pixels in the NLC array is measaured with the other pixels having varying settings. Fig.12 shows via a CCD camera a particular NLC pixel that is turned on and turned off, with the surrounding pixels having the opposite settings. In general, the pixel on/off optical isolation for this device comes to be around 128 :1 or 21 dB. This NLC device is interfaced to a computer controlled driver board that generates NLC drive signals using a 8-bit D-A converter. Thus, for a full 0-2π phase control for the device, at most a 256 :1 amplitude control is possible. For a 0-π phase control required for a pixel full-on full-off response, 128 : 1 control is possible via our driver board. Thus, our NLC pixel on/off isolation measurement is restricted by the digital nature of the drive signal generation electronics. For high on/off isolation from NLCs, the drive signals should have high resolution amplitude/level control that is currently being developed.

5. CONCLUSION

We have experimentally demonstrated a potentially low insertion loss, high optical isolation (> 30 dB) NLC-based OTDU that is a basic building block for the NLC-based optical time delay control system for wide bandwidth phased array antennas. Various SLM-based reversible OTDUs are introduced that can provide both the phase bits and the true-time delay bits for a transmit/receive mode phased array antenna. The phase bits are also introduced via time delay, and depend on the particular antenna center frequency. In this way, all the antenna control functions can be remotely located in an optical beamformer, making the antenna array face lighter and smaller for greater mobility. Remoting is achieved via multi-fiber links that are connected to compact optoelectronic transceiver modules that contain a DFB laser and a high speed photodiode, such as shown in Fig.13. Signal splitting/combining required in the transmit/receive mode of the antenna can be accomplished by a combination of electrical and free-space lens-based optical splitting/combining networks. The free-space nature of the proposed OTDUs allows for advanced receive beamforming such as forming multiple simultaneous receive beams, and monopulse beamforming.

6. REFERENCES

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Table.1 Highlights of some of the features and limitations of the three types of delay lines.

Feature /Limitation	Cascaded Free-Space	Folded-Fiber Type	Single Switching Layer
Compactness	Medium Compactness design; 100, 10-bit delay lines in a 1" H X 24" L X 10 " W package	Ultracompact; ten, 10 bit delay lines in a 1 cubic inch volume	Medium high compactness; NLC arrays require less packaging as all on one substrate
Optical Losses	Very Low: < 0.45 dB/bit; Efficient free-space coupling	Moderately low: 1 dB/bit; Use of PM-fibers increases coupling losses	Very Low: < 0.45 dB/bit; Efficient free-space coupling
Interconnection Complexity	Simple free-space interconnects, imaging bulk optics can also be used	Careful, time consuming PM-fiber alignment required	Simple free-space interconnects, imaging bulk optics can also be used
Channel /Bits Upgrade Capability; Redundancy	Easy upgrades due to 3-D free-space cascaded design	Moderately Easy Upgrades; Fibers increase complexity	Very Easy upgrades due to 3-D free-space design using single optical switching layer
Components Required	Large number of bulk optics and several NLC devices	Very little bulk optics and few NLC devices; but large number of PM-fibers	Large number of bulk optics and only one large area NLC device

Table. 2 showing measured optical transmision at 633 nm of various optical components.

Component	Transmission (%)	AR Coating at 550 nm
Cube PBS (straight beam)	94	yes
Cube PBS (deflected beam)	96	yes
Sheet Polarizer	71	no
Thompson Prism Polarizer	94	yes

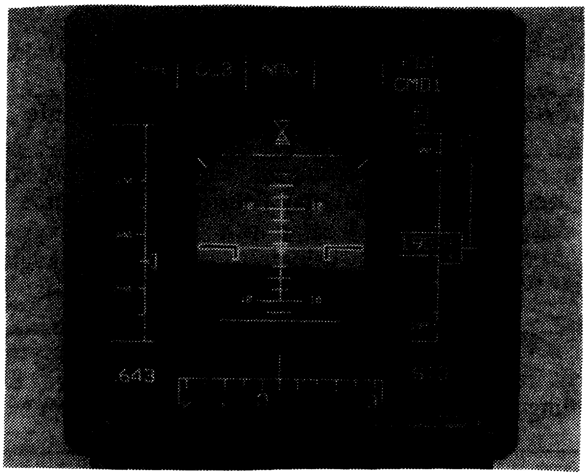

Fig.1 The 1-Mega pixel NLC Display fabricated at GECRD for the USAF F-16 and ATF cockpit displays.

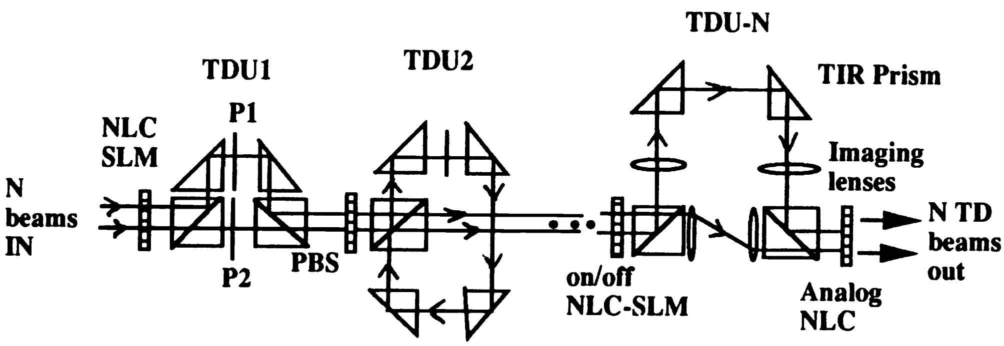

Fig.2 The cascaded free-space type multichannel optical switched delay line.

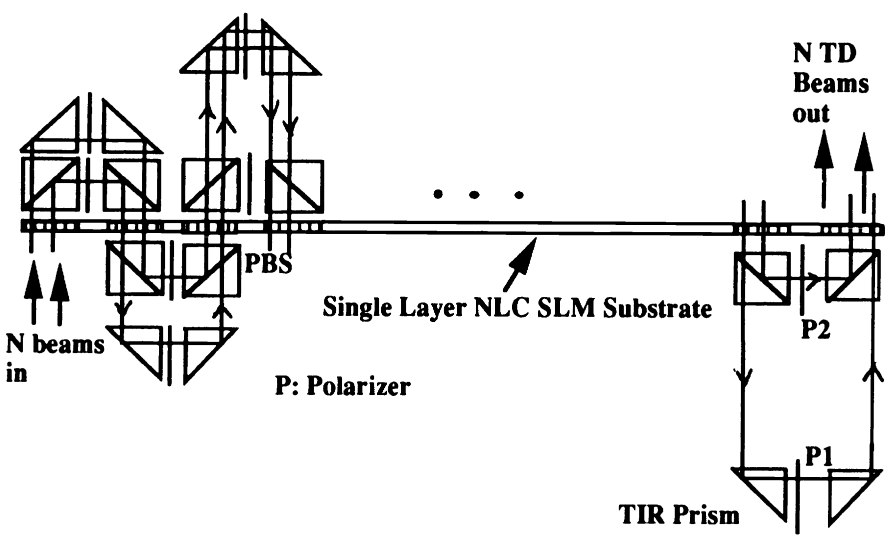

Fig.3. The single NLC array substrate multichannel free-space optical delay line.

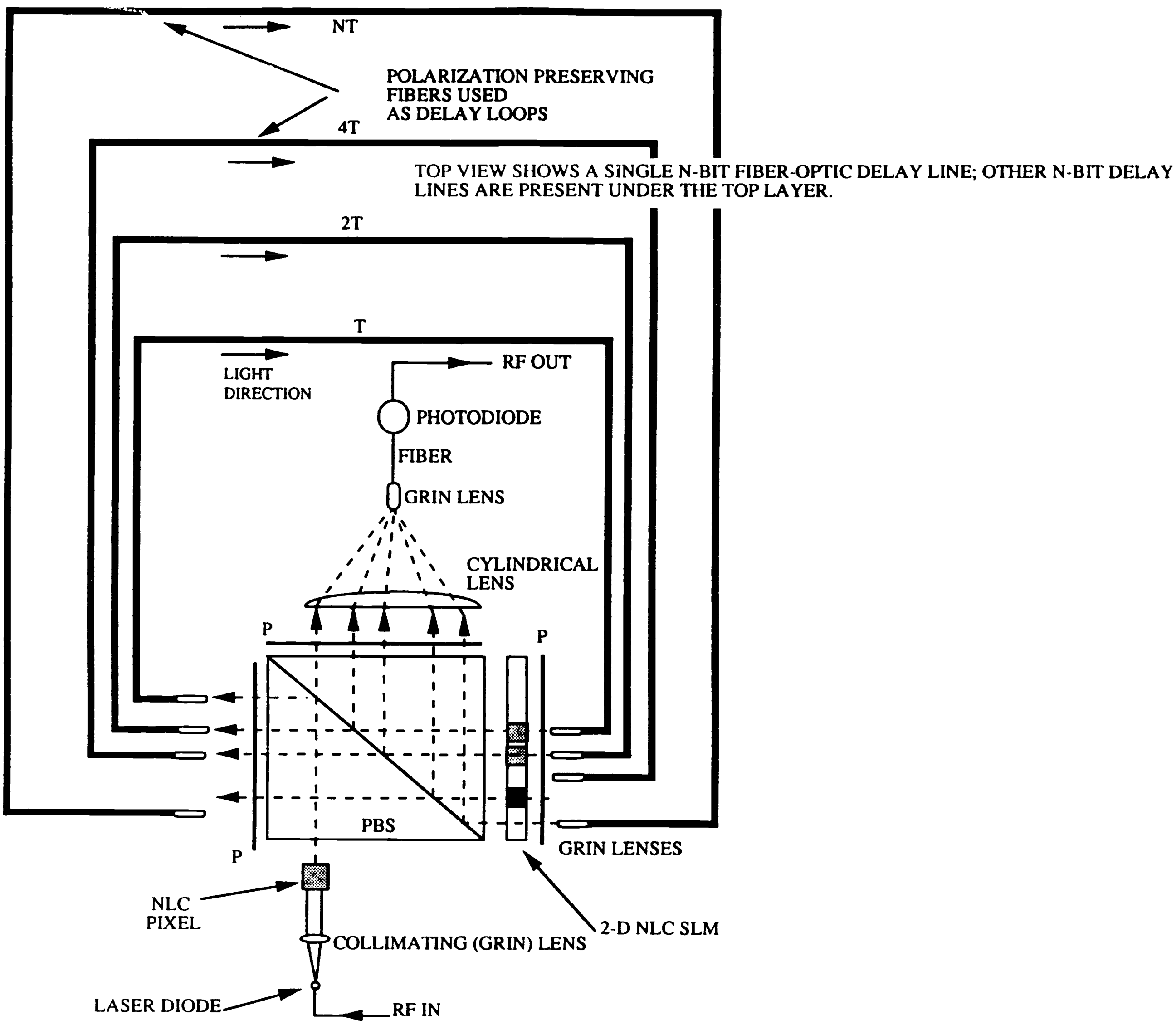

Fig.4 The folded-fiber type multichannel optical switched delay line.

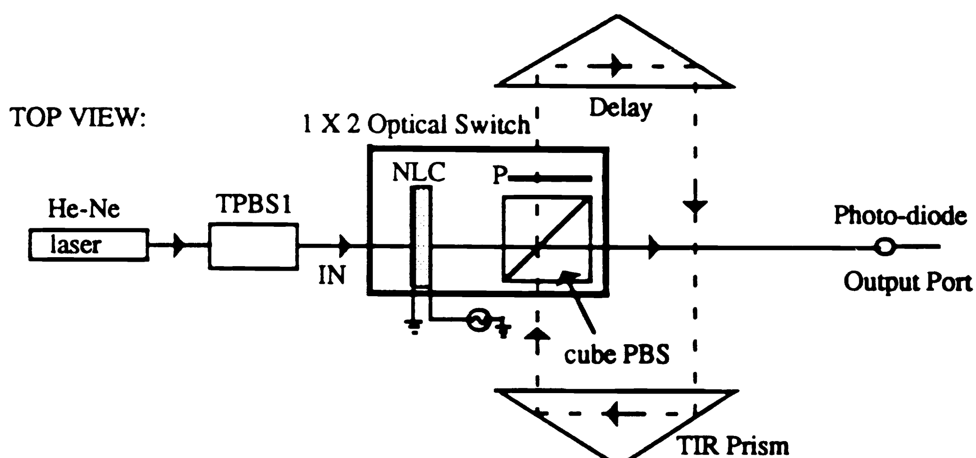

Fig.5 A typical free-space optical time delay unit (OTDU).

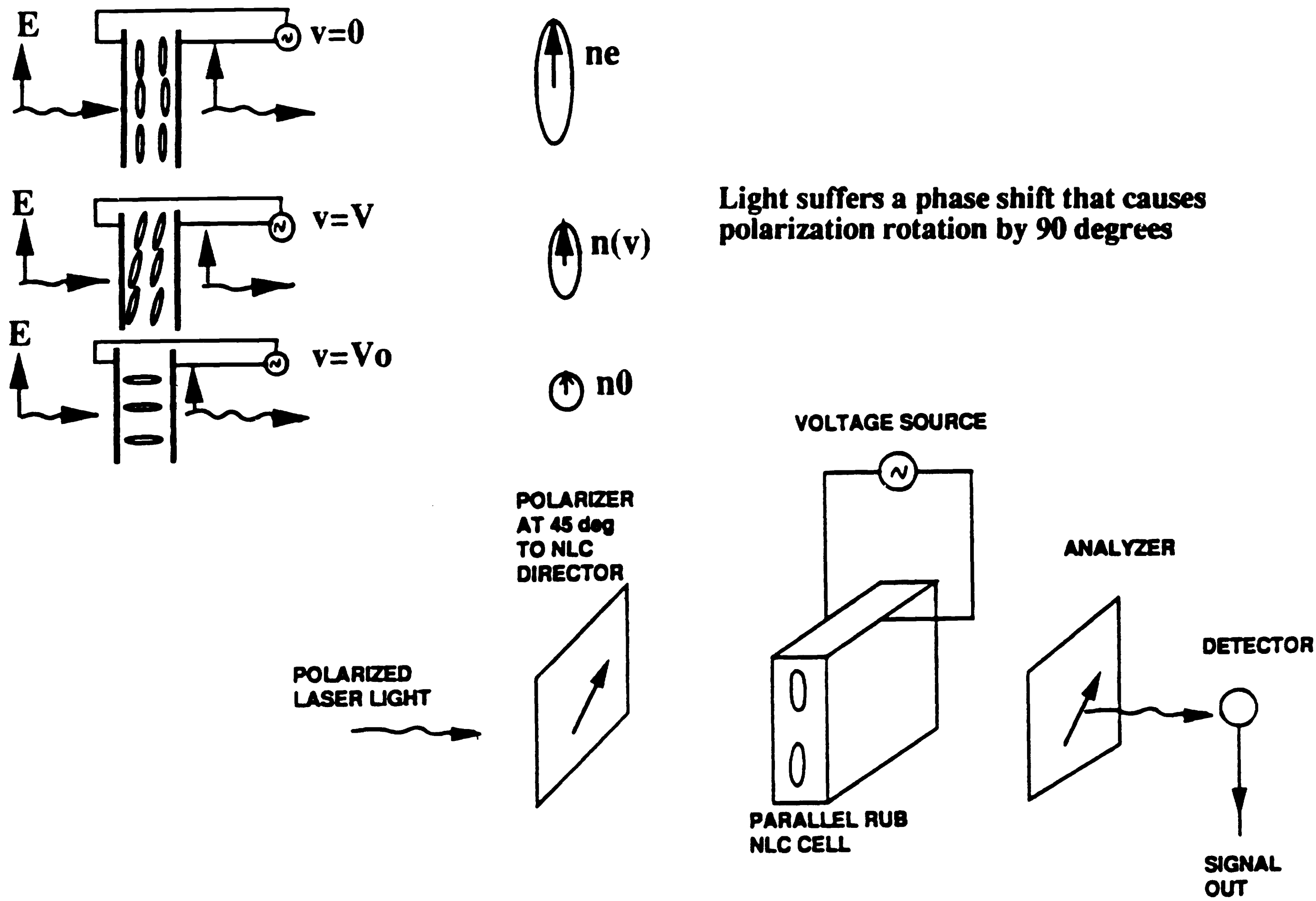

Fig.6 The optical switching operation via an NLC cell is based on polarization rotation of light beams by the electrically controlled NLC birefringent medium. The linearly polarized input light is incident at 45 degrees to the nematic director of the NLC cell for optimum on/off isolation.

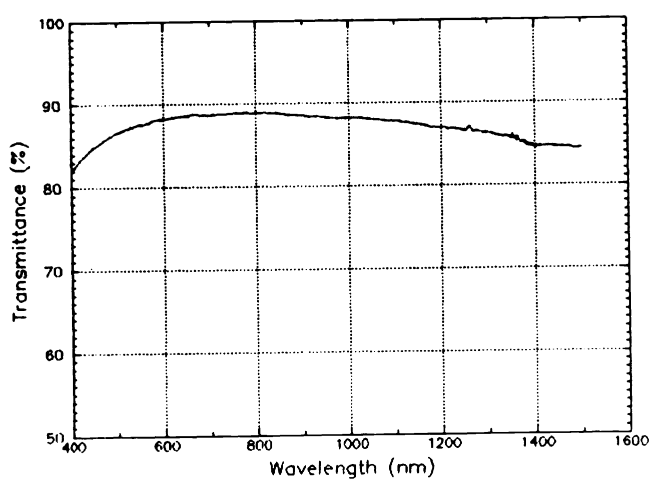

Fig.7 A transmission vs. wavelength graph generated using a spectrometer for a 6 μm thick NLC cell using ordinary glass material similar to Corning 7059 glass.

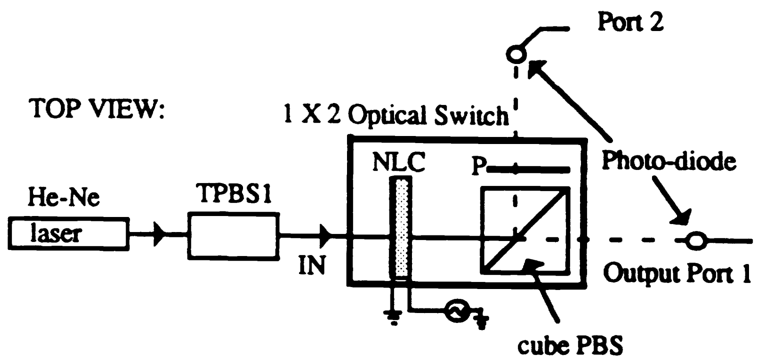

Fig.8 The set-up that forms the 1 X 2 NLC optical switch that is the building block for the OTDU.

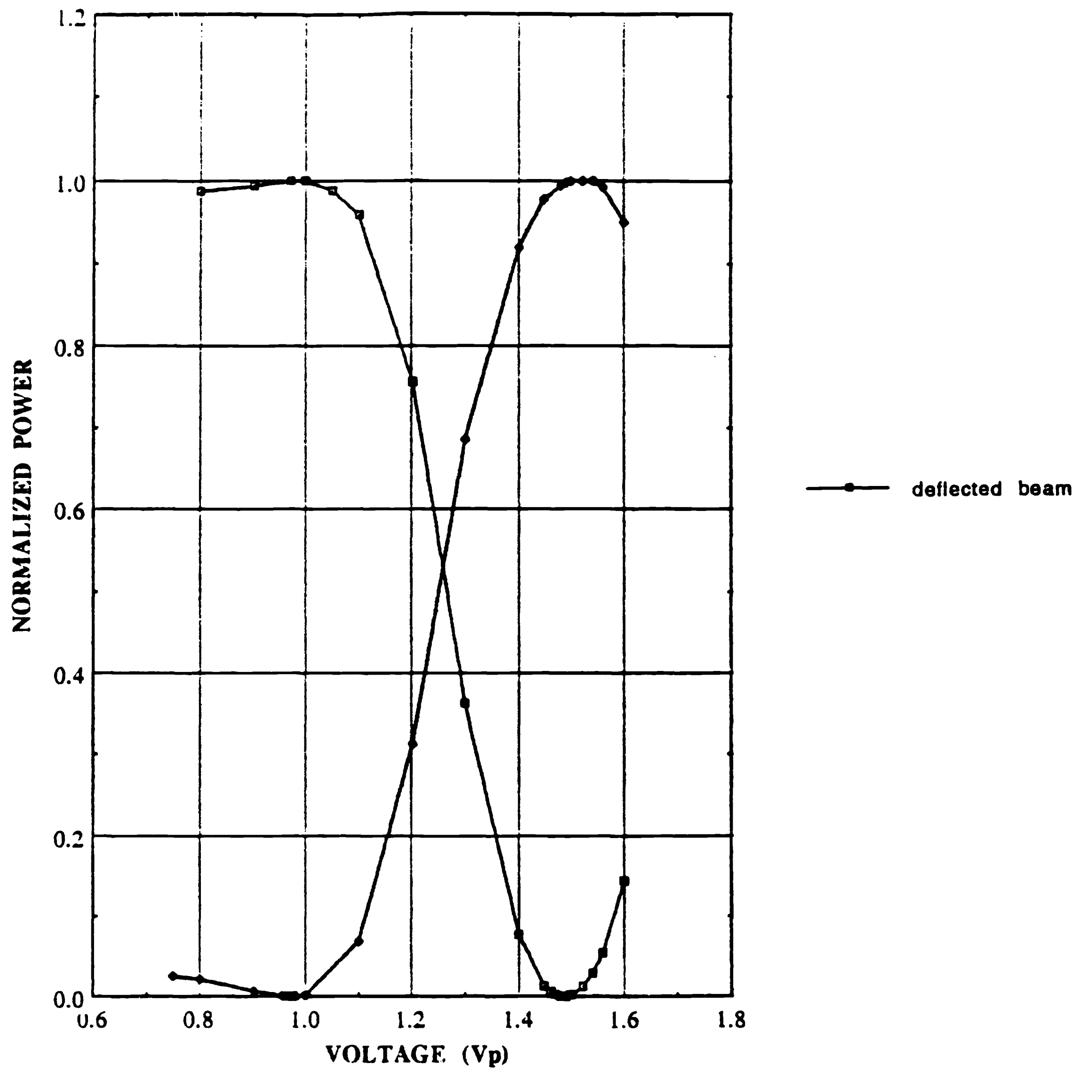

Fig.9 The normalized data plot of the light out of the two output ports of the 1 X 2 NLC optical switch, showing the desired reciprocal behavior. The measured straight beam optical contrast ratio is 3,704 :1 which is 35.68 dB optical isolation or 71.37 dB rf isolation. The measured 90 degree deflected beam optical contrast ratio is 3,446 :1 which is 35.37 dB optical isolation or 70.75 dB rf isolation.

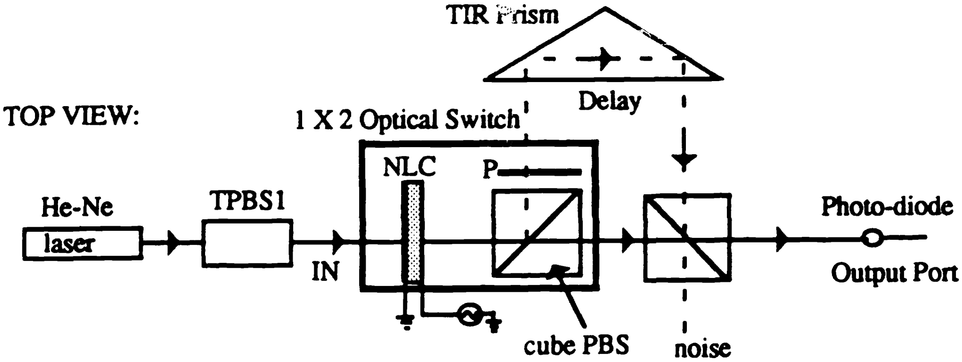

Fig.10 An alternate configuration for an OTDU experimentally demonstrated in the laboratory.

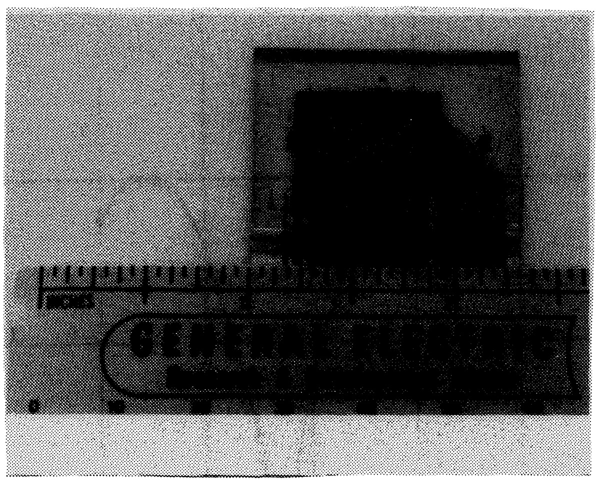

Fig.11 A 1500 pixel TFT driven NLC SLM fabricated at GECRD.

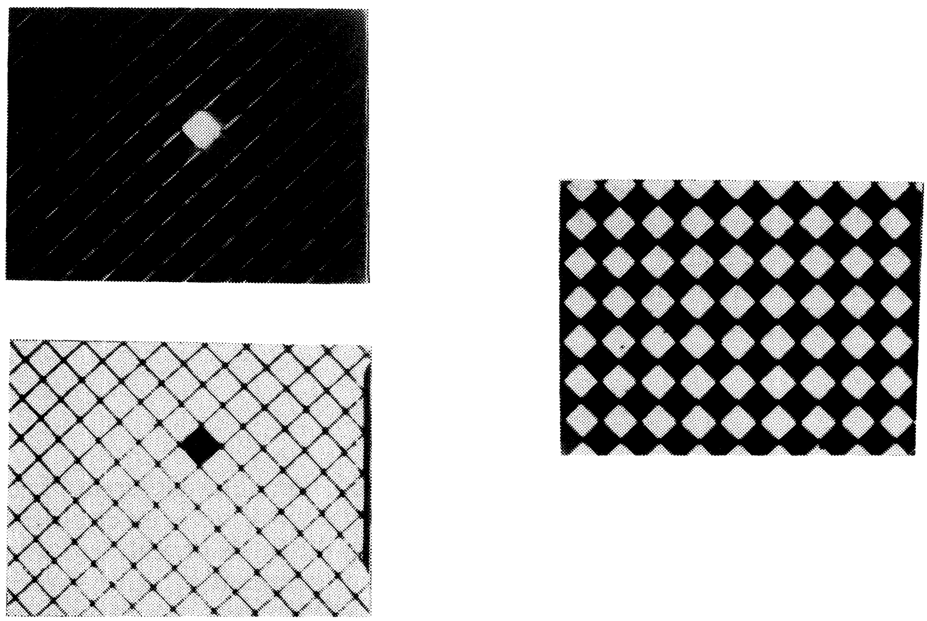

Fig.12 The CCD camera images of the 1500 pixel NLC device when a specific pixel is tested for maximum on/off optical isolation when the surrounding pixels have opposite settngs. A 128 : 1 (21 dB) optical contrast is measured, limited by the digital nature of the NLC driver electronics.

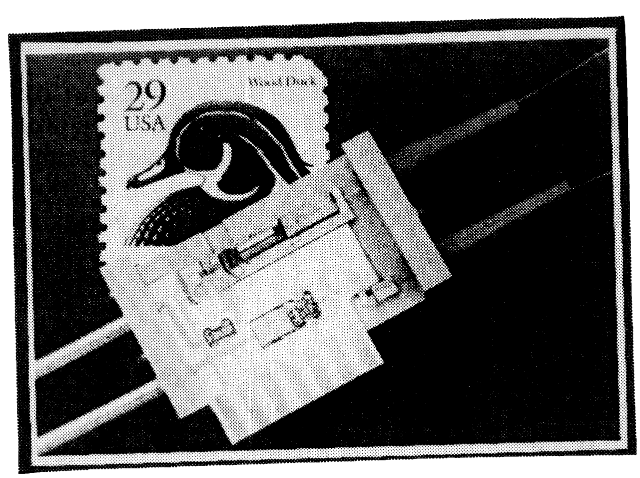

Fig.13 A compact S/C band optoelectronic transceiver module fabricated at GE Aerospace (now Martin-Marietta) Electronics Laboratory using silicon optical bench technology.